Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [A COFDM Scheme for IEEE's High Rate WPAN]
Date Submitted: [July 2000]
Source: [David Skellern, John O'Sullivan & Andrew Myles] Company: [Radiata Communications]
Address: [1 Julius Ave, North Ryde, Sydney NSW 2113 Australia]
Voice:[+61 2 8874 5404], FAX: [+61 2 8874 5401], email:[daves@ieee.org]

Re: [TG3 PHY/MAC layer submission]

Abstract: [This contribution is a proposal for a high rate WPAN (up to 41 Mbit/s) operating in the 5GHz U-NII bands. The system uses Coded Orthogonal Frequency Division Multiplex modulation and is similar to the 802.11a standard with some major simplifications that allow a lower complexity, low cost receiver. The submission also proposes the use of the 802.11 MAC with specific enhancements for PANs]

Purpose: [Response to WPAN-TG3 Call for Proposals]

Notice: This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.

Release: The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

A COFDM Scheme for IEEE's High Rate WPAN

11 July 2000

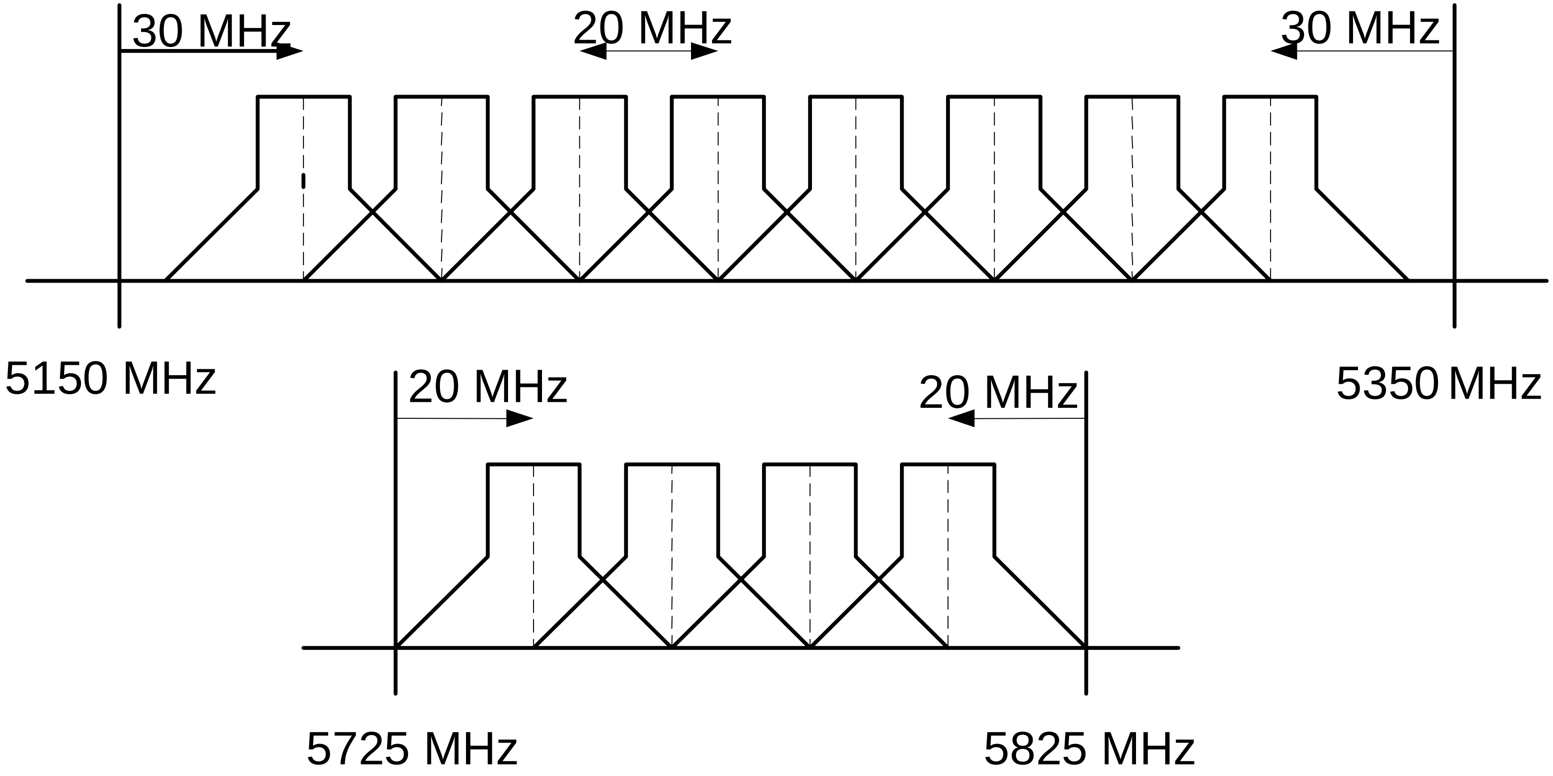
PMD - OFDM Parameters

Propose use of a COFDM system with 52 data carriers in a 20 MHz channel with 400ns guard time for multipath signals.

Parameter	*Value*
Sampling rate f_s=1/T	20 MHz
Useful symbol part duration	64*T 3.2 us
Cyclic prefix duration	8*T 0.4 us
Symbol interval	72*T 3.6 us
Number of data sub-carriers	52
Number of pilot sub-carriers	0
Total number of sub-carriers	52
Sub-carrier spacing	0.3125 MHz
Spacing between the two outmost sub-carriers	16.25 MHz

PMD - Channels

Use same channels as IEEE 802.11a: 12 channels in the US non-contiguous 5 GHz Unlicensed National Information Infrastructure bands



PMD - PHY Rates

The proposal provides 14, 29 & 43 Mbit/s using repetition coded DQPSK, trellis coded D8PSK modulations and uncoded D8PSK, with scrambling and length 52 interleaving

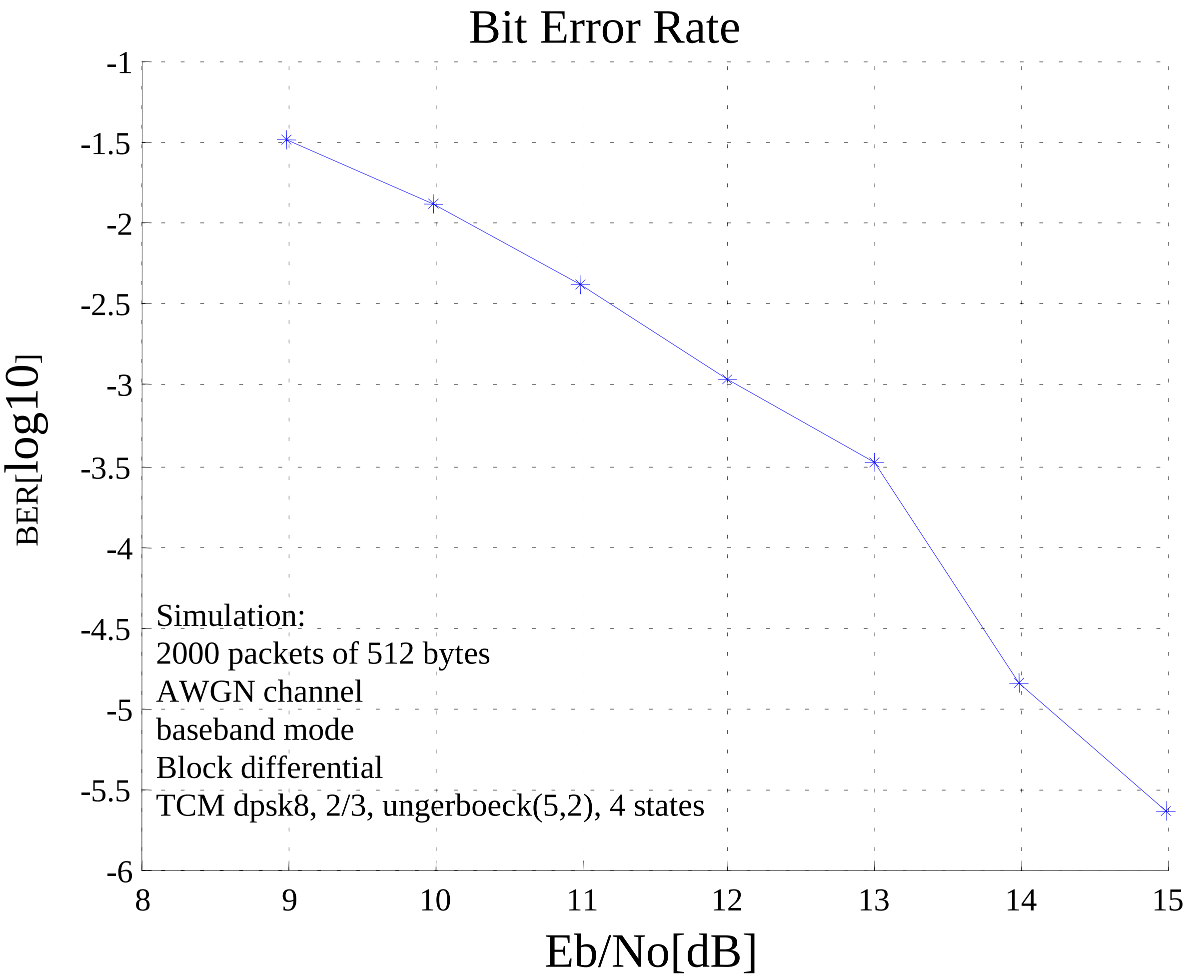
- Range for 1mW Tx power, 0 dBi Tx antenna gain, 0 dBi Rx antenna gain, 7 dB Rx NF and path loss based on ITU P.1238:

Data Rate Mbit/s	Modulation/ Code	Coding rate	coded bits per subcarrier	Eb/N0 BER 10^-5	C/N BER 10^-5	Range m (Free Space)	Range m (ITU 0 Floor)	Range m (ITU 1 Floor) [1]
14.4	DQPSK 2-rep	1/2	2	9.5	12.5	89	18	6
28.9	D8PSK trellis (4s)	2/3	3	14.0	17.0	53	13	4
43.3	D8PSK uncoded	1	3	15.8	20.6	35	10	3

[1] floor attenuation = 16dB

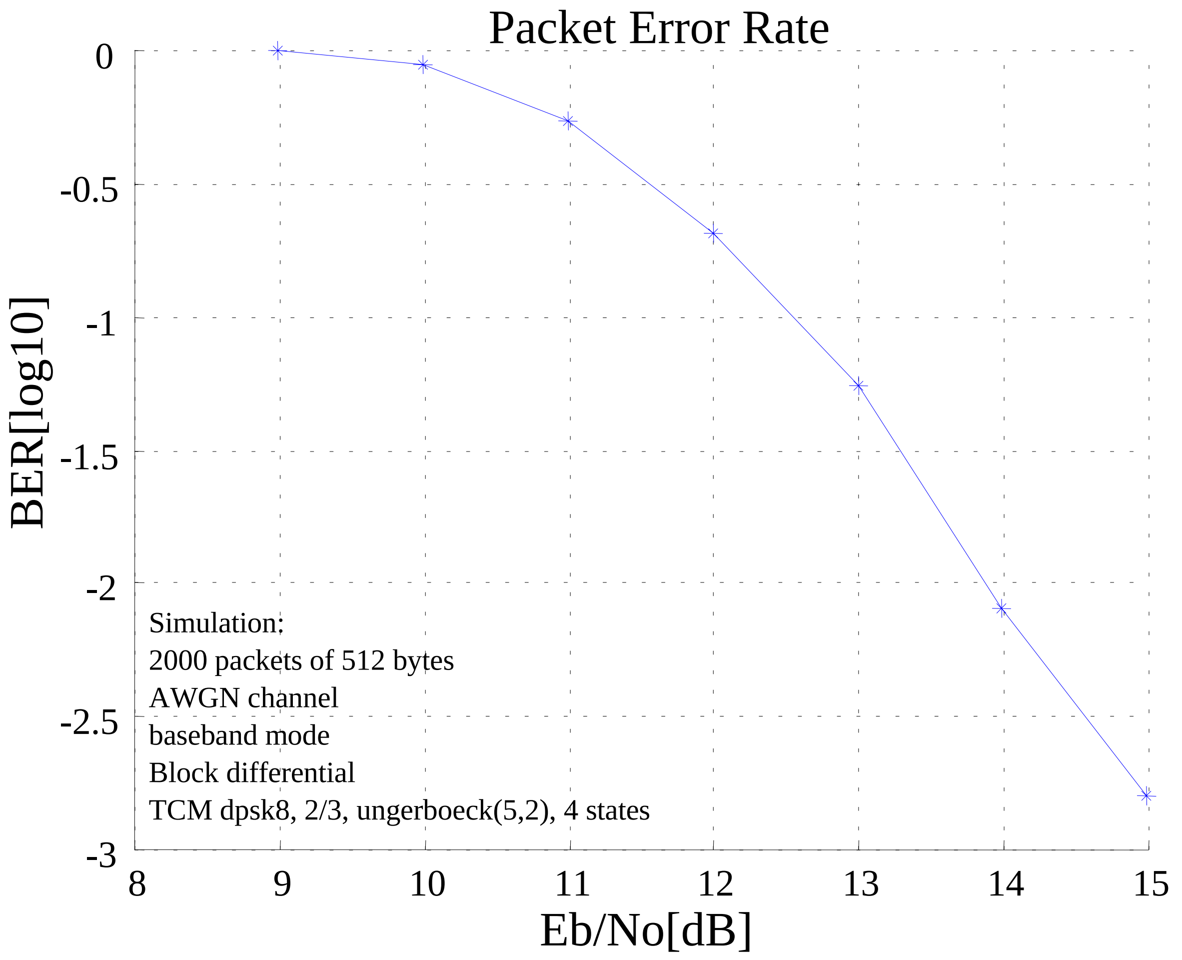
BER Performance

BER for 28.9 Mbit/s rate and AWGN channel



PER Performance

PER (512 bytes) for 28.9 Mbit/s rate and AWGN channel



PMD - PHY Rates

A variety of other codes were investigated, all with interleaving, including a (2,1,5) convolutional code with and without puncturing, and a rate 1/2 ring code over Z8

- Range for 1mW Tx power, 0 dBi Tx antenna gain, 0 dBi Rx antenna gain, 7 dB Rx NF and path loss based on ITU P.1238:

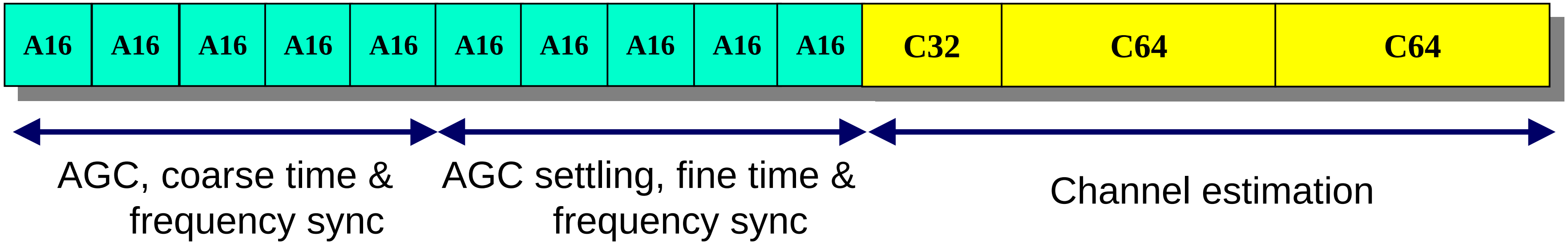
Data Rate Mbit/s	*Modulation/ Code*	*Coding rate*	*coded bits per subcarrier*	*Eb/N0 BER 10^-5*	*C/N BER 10^-5*	*Range m (Free Space)*	*Range m (ITU 0 Floor)*	*Range m (ITU 1 Floor)* [1]
7.2	DBPSK conv (16s)	1/2	1	4.2	4.2	231	33	10
10.8	DBPSK conv (16s)	3/4	1	5.1	6.9	170	27	8
14.4	DQPSK conv (16s)	1/2	2	9	9.0	133	23	7
21.7	D8PSK ring code (16s)	1/2	3	8.2	10.0	119	22	7
21.7	DQPSK conv (16s)	3/4	2	10	11.8	97	19	6
28.9	D8PSK trellis (16s)	2/3	3	10.0	13.0	84	17	5
28.9	DQPSK uncoded	1	2	12.5	15.5	63	14	4
43.3	D8PSK uncoded	1	3	15.8	20.6	35	10	3

[1] **floor attenuation = 16dB**

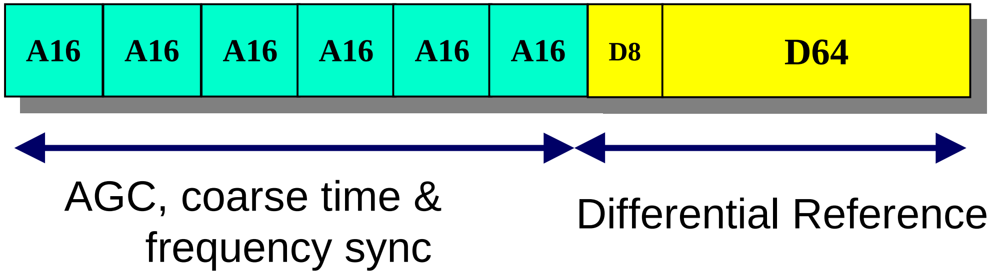
PLCP - Preamble & sync

Differential modulation greatly simplifies sync and preamble

- **802.11a PLCP preamble (16μs)**



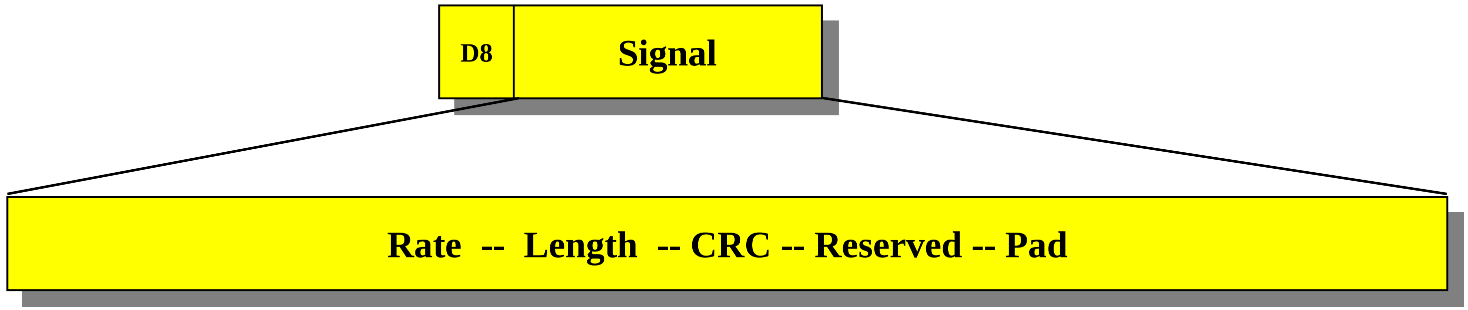
- **802.15.3 preamble proposal (8.4μs)**



PLCP - Signal field

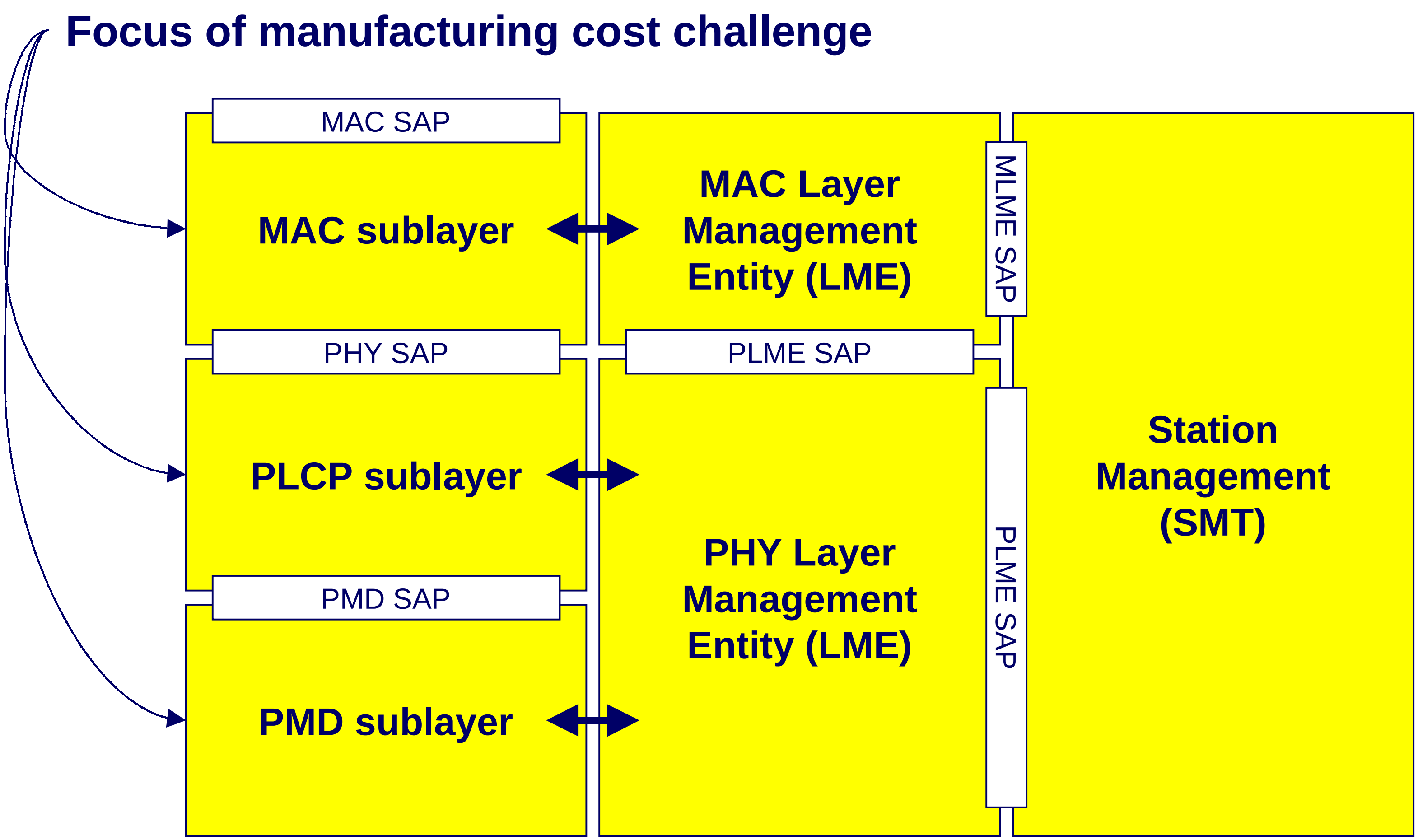
One OFDM symbol (3.6μs) is allocated for PLCP signalling

- The PLCP signal field is a total 104 bits including coding
- The proposal is to send it as repetition coded QPSK
- This avoids long decoder delay and simplifies the receiver structure
- CRC error detection protects against signal field errors
- Details on fields for future work



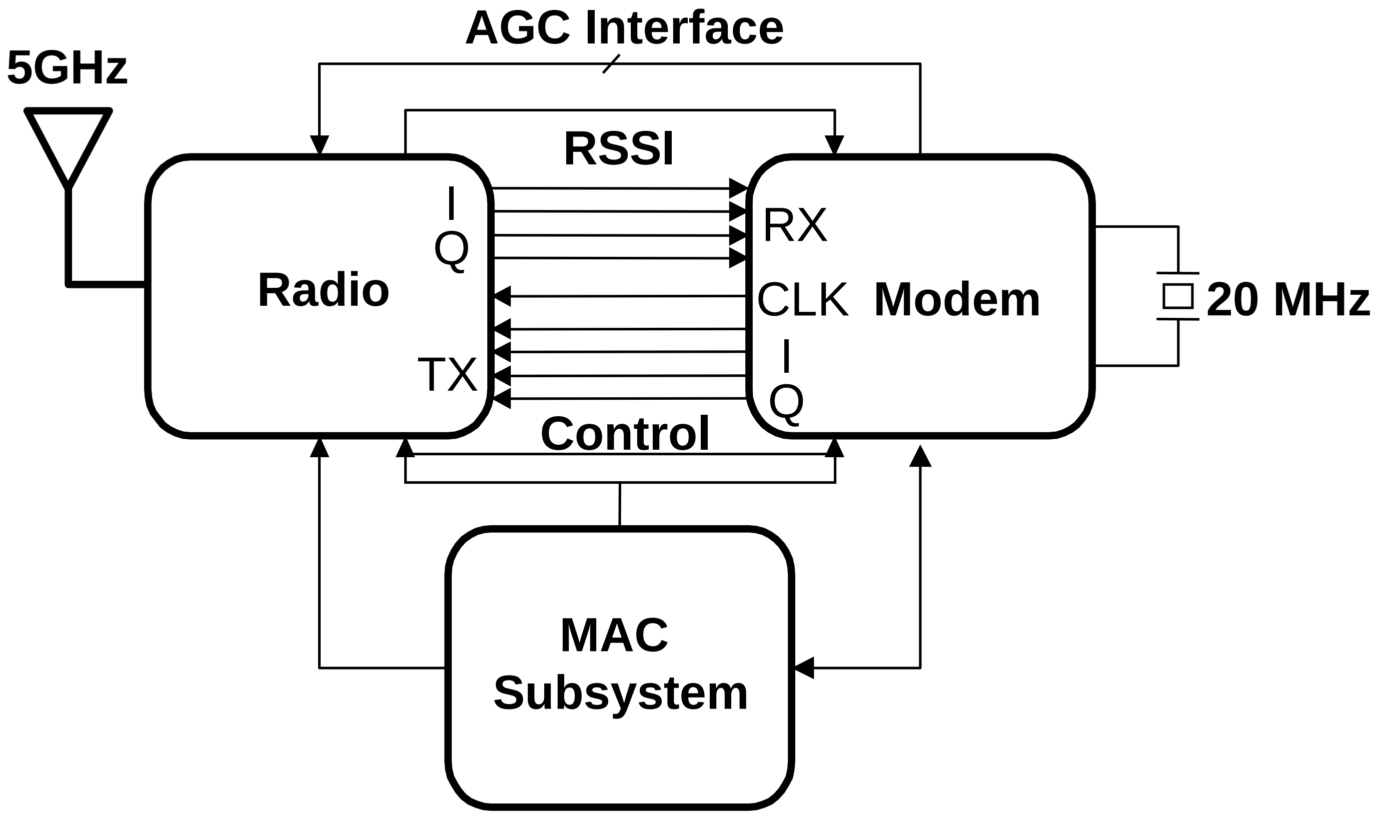
2.1 Unit Manufacturing Cost

Suggest node structure as shown below - an elaboration of Figure 1 of the TG3 Criteria Definitions document



2.1 Unit Manufacturing Cost

A NIC consists of a three main functional components with minimal passive and no extra active components



2.1 Unit Manufacturing Cost

All active components can be implemented in CMOS - initially a modem/MAC chip and an RF chip, and eventually a single chip

- The modem is order 80k gates (scaling from our implementations of 16-tone differential and full 802.11a systems)
- Add Dual (I/Q) 8-bit ADCs and DACs
- An appropriate 802.11-like MAC is order 60k gates plus memory
- A 0dBm, 7dB NF 5 GHz dual conversion transceiver including VCOs and filters is now possible in 0.18um CMOS in a chip area of less than $20mm^2$ with good yield
- CMOS cost curves will guarantee the continued price reductions needed to achieve target consumer cost levels

2.2 Signal Robustness

- **2.2.2. Interference and Susceptibility**
  - To be determined. COFDM is relatively tolerant of interference. Cochannel interference is determined by the C/N of the modulation employed on each carrier. Adjacent channel is largely determined by specifics of the implementation.
- **2.2.3. Intermodulation Resistance**
  - Intermodulation is largely determined by the particular receiver implementation dynamic range.
  - Subcarrier intermodulation requires operation in a relatively linear region.
  - Coded D8PSK requires backoff of ~5dB from 1dB compression point for non-linearised PA or ~3dB for a linearised PA
- **2.2.4. Jamming Resistance**
  - TBD
- **2.2.5. Multiple Access**
  - The existence of multiple channels allows multiple systems to coexist without interference, one of each channel. The system filtering, proposed to be the same as 802..11a, ensures low non-interfering out-of-channel emissions
- **2.2.6. Coexistence**
  - The only potentially interfering system is 802.11a - use of an 802.11-style MAC will ensure coexistence

2.3 Interoperability

The proposed system is interoperable with 802.15.1 only by addition of an 802.15.1 stack and bridging function

- The frequency band is 5 GHz cf Bluetooth at 2.4 GHz
  - A separate radio is needed
- The Bluetooth MAC differs greatly from the proposed MAC
  - A separate 802.15.1 MAC implementation is needed
- If we add an 802.15.1 stack, a bridging function is needed between the it and the 802.15.3 stack.

2.4 Technical Feasibility

Eminently feasible

- **2.4.1. Manufactureability**
  - Currently available CMOS processes are suitable
- **2.4.2. Time to Market**
  - Modem and MAC chips of greater complexity have been demonstrated
  - Prototype 5 GHz RF CMOS transceivers have been demonstrated and production versions are in development with demonstrations expected before the end of 2000
- **2.4.3. Regulatory Impact**
  - TRUE (U-NII rules)
- **2.4.4. Maturity of Solution**
  - COFDM systems of this type have been built and run by several groups and companies around the world

2.5 Scalability

While COFDM is very scalable, the parameters and functionality for this proposal are optimised for the cost/data rate/complexity/power tradeoff given the relatively less demanding PAN compared to a LAN.

- **Power consumption**
  - Can be controlled by variable transmit power
- **Data Rate**
  - Data rate in this proposal can be scaled by increasing the clock rate and, consequently, bandwidth and power consumption (there is effectively an upper limit on bits/Hz for a low complexity, low power design)
- **Frequency Band of Operation**
  - Operation in any frequency band is possible - 5 GHz is attractive because of the low level of interfering signals
- **Cost**
  - The proposal is optimised for cost - reductions will be incremental and process and volume driven
- **Function**
  - The proposal functionality is optimised for cost

An 802.15.3 MAC based on the 802.11 MAC

11 July 2000

MAC choices - general approaches evaluated

Modifying an existing wireless MAC protocol is the best way to deliver the required features

Approach	Positives	Negatives
Use an existing (im-plemented) MAC design	• Limited additional design work required • The properties (good and bad) of the protocol are well known • Existing implementations can be leveraged	• It is unlikely the protocol will satisfy all of 802.15.3's requirements
Modify an existing (im-plemented) MAC design	• The basis has already been designed • The properties (good and bad) of the protocol are well known • Can leverage existing knowledge of protocol to make 802.15.3 specific modifications • Existing implementations can be leveraged	• The modified protocol may still compromise some required 802.15.3 features
Design new (currently un-implemented) MAC	• Starting with a "clean sheet" maximises possibility that result satisfies requirements • Can leverage the best properties of all existing MAC protocols	• The design process is likely to be slow and painful with high risk of "failure" • The result is likely to be no better than existing MAC's; **MAC design is hard!** • The time for implementations to be ready is likely to be long

Summary

The 802.15.3 requirements, as currently specified, will be satisfied by modifying an existing wireless MAC protocol, 802.11

- What are the requirements?
  - The P802.15 WPAN working group has specified some general and MAC specific criteria for evaluating potential 802.15.3 MAC solutions
- What is the best approach to satisfy the requirements?
  - We believe that extending/modifying an existing wireless MAC protocol is the best way to deliver the required features
    - design reuse
    - potential for amortisation of cost over larger volume
- Which existing MAC could be modified?
  - Our assessment of the criteria is that the 802.11 MAC is a reasonable candidate on which to base the 802.15.3 MAC

The P802.15 WPAN working group has specified some general criteria for evaluating potential 802.15.3 MAC solutions

- Multiple access
  - Support for multiple 802.15.3 networks sharing the same "channel"
- Interoperability
  - Support for interoperability (at some level) with 802.15.1
- Technical feasibility
  - Enable fast time to market at low risk
- Scalability
  - Ability of the solution to be optimised or modified when protocol parameters are changed (eg data rate, frequency, cost, function)

Requirements – MAC specific criteria

The P802.15 WPAN working group has specified some MAC specific criteria for evaluating potential 802.15.3 MAC solutions

- **Transparency**
  - Provide transparent access to upper layer protocols, eg TCP/IP
- **Ease of use**
  - Unique 48 bit address to identify each node
  - Simple and fast network join procedures
  - Allow device registration by class without user intervention
- **Delivered data throughput**
  - >20Mbit/s delivered data throughput
- **Data transfer types**
  - Asynchronous and new "*Isochronous*"
- **Quality of service**
  - Service contracts for bursty, bulk and real-time traffic
- **Topology**
  - At least 7 active connections
  - Ad hoc networks
  - Access to a portal
- **Reliability**
  - Provide recovery mechanisms for loss of any required "master" or loss of link
- **Power management**
  - Appropriate to application (sleep, snooze, rest)
- **Power Consumption**
  - MAC controller and memory
- **Security**
  - Support authentication of stations
  - Support privacy of messages

Requirements – More description needed

An expanded description of 802.15.3 functional requirements to design the MAC

- We need to elaborate the differences between 802.15.3 and a standard wireless LAN to complete a design
  - eg the functional differences might be highlighted by a set of usage scenarios such as those described by the BlueTooth documentation

BUT

- It seems that a variety of simple modifications could be made to 802.11 to give a better match to 802.15.3 requirements

AND

- The 802.11 working group is already working to improve QoS and security aspects of the 802.11 MAC

802.11 based solution – General criteria

The 802.11 MAC operating with an 802.11a-like PHY satisfies most of the general 802.15.3 criteria

		802.11 mode		
		BSS		IBSS
Category	**802.15.3 requirement**	**PCF**	**DCF**	**DCF**
Multiple access	Support for multiple 802.15.3 networks sharing “channel”	partial	partial	partial
Interoperability	Support for interoperability (at some level) with 802.15.1	✓	✓	✓
Technical feasibility	Allow fast time to market at low risk	✓	✓	✓
Scalability	Ability of the solution to be optimised or modified when protocol parameters are changed	✓	✓	✓

802.11 based solution – MAC criteria - 1

The 802.11 MAC operating with an 802.11a-like PHY satisfies most of the MAC specific 802.15.3 criteria

		802.11 mode		
		BSS		IBSS
Category	802.15.3 requirement	PCF	DCF	DCF
Transparency	Provide transparent access to upper layer protocols	✓	✓	✓
Ease of use	Support unique 48 bit address to identify each node	✓	✓	✓
	Provide simple and fast network join procedures	✓	✓	✓
	Device registration by class without user intervention	partial	partial	partial
Throughput	Provide at least 20Mbit/s delivered data throughput	✓	✗	✗
QoS	Support for QoS for bursty, bulk and real-time traffic	partial	✗	✗
Power	Support power management	✓	✓	✓

802.11 based solution – MAC criteria - 2

The 802.11 MAC operating with an 802.11a-like PHY satisfies most of the MAC specific 802.15.3 criteria

Category	802.15.3 requirement	802.11 mode		
		BSS		IBSS
		PCF	DCF	DCF
Topology	Support of at least 7 active connections	✓	✓	✓
	Support for ad hoc networks	✗	✗	✓
	Support of access to a portal	✓	✓	✓
Reliability	Provide recovery mechanisms for loss of “master”	partial	partial	partial
	Provide recovery mechanism for loss of a link	partial	partial	partial
Security	Support authentication of stations	partial	partial	partial
	Support privacy of messages	partial	partial	partial

802.11 based solution – Evaluation - Summary

A variety of simple modifications could be made to 802.11 to ensure a better match to 802.15.3 requirements

- 802.11 may require extensions to ensure support for:
  - overlapping networks
  - interfaces other than 802.2
  - device registration by class
  - PCF in all environments to enable 20Mbit/s throughput at all times
  - QoS guarantees
  - *ad hoc* networks that provide 20Mbit/s throughput, reliability and QoS
  - master redundancy
  - more extensive security

802.11 based solution – Evaluation– Multiple access

802.11 may require extensions to ensure support for overlapping networks

- The 802.11 MAC specifies methods to avoid interference when multiple BSS's are operating in the same channel
- The currently defined mechanisms do not work in all circumstances, particularly in PCF mode
- Various techniques to avoid overlap interference have been used by other MACs or discussed by the 802.11 working group:
  - manual frequency planning
  - dynamic frequency selection
  - management protocols

802.11 based solution – Evaluation– Transparency

802.11 may require extensions to ensure support for interfaces other than IEEE 802.2 LLC

- The 802.11 standard specifies transparency:
  - "IEEE 802.11 is required to appear to higher layers [logical link control (LLC)] as a current style IEEE 802 LAN" (section 5.1.1.4)
- Interfaces to other higher layers could also be defined, if necessary, in a similar way to those in Bluetooth; additional interfaces could provide for:
  - audio
  - video
  - service discovery protocols
  - telephony control
  - etc

802.11 based solution – Evaluation– Ease of use

802.11 may require extensions to ensure support for device registration by class

- 802.11 provides device registration using an authentication (IBSS and BSS) and association (BSS only) procedures
- 802.11 does not include a facility to search for and register with devices offering particular classes of service
- These facilities could be added by:
  - Extension of existing management frames
  - Definition of a service discovery protocol (possibly similar to Bluetooth)

802.11 based solution – Evaluation– QoS

802.11 may require extensions to ensure support for QoS guarantees

- In the current version of the 802.11 MAC:
  - DCF mode can only provide provide very limited QoS guarantees
  - PCF mode defines a basis of a QoS infrastructure but requires further work
- Levels of guarantee need to be teased out by 802.15.3
- QoS features could be added to 802.11 using any one of a number of existing proposals (mainly based on PCF) to the 802.11 working group by:
  - Sharewave
  - AT&T
  - Lucent
  - Intel
  - etc

802.11 based solution – Evaluation– Topology

802.11 may require extensions to ensure support for *ad hoc* networks that provide 20Mbit/s throughput, reliability and QoS

- In the current version of the 802.11 MAC *ad hoc* networks are provided using DCF mode in an IBSS
- However, DCF does not provide sufficient throughput; it may not provide sufficient QoS features
- To ensure ad hoc functionality with sufficient throughput, reliability and QoS 802.11 may require extensions that add:
  - *ad hoc* networks based on PCF mode (for throughput and QoS)
  - direct STA to STA communications in a BSS (for throughput)
  - master redundancy (for reliability)
  - BSS overlap resolution (for reliability)

802.11 based solution – Evaluation– Reliability

802.11 may require extensions to ensure support for master redundancy

- – Master redundancy is used to mitigate a "single point of failure"
- – Currently, 802.11 has no explicit master redundancy in BSS mode; none is required in IBSS mode
- – Any master redundancy that does occur is slow and relies on rebuilding the BSS from scratch
- – Master redundancy could be added by defining new protocols that keep one or more stations in a "hot standby" mode

802.11 may require extensions to ensure support for more extensive security

- The 802.11 MAC currently defines authentication and privacy based on RC4 using 40 bit shared keys
- Possible extensions might include:
  - additional algorithms
  - longer key lengths
  - mutual authentication
  - compatibility with Internet security framework
- A variety of possible security extension proposals along these lines have already been discussed by 802.11 TGe

802.11 based solution – Improvement process

The 802.11 working group is already working to improve many aspects of the 802.11 MAC

- The 802.11 working group is addressing many of the issues required to satisfy the 802.15.3 requirements already including:
  - QoS
  - master redundancy
  - overlapping BSS’s
  - direct STA to STA communications
  - security
- Other changes required to satisfy 802.15.3 requirements would also probably be useful additions to 802.11 and so welcomed by the 802.11 working group

3.8 Power Consumption of MAC Controller

Budget 0.5W declining with time as more power efficient processors and processor/memory structures evolve

- MAC controller power consumption is estimated at 300 mW
- MUST add additional 200mW for memory - based on experience of current controllers

802.15.3 PHY Criteria Notes

11 July 2000

4.1 Size and Form Factor

Given a single or two chip solution there are no fundamental impediments to achieving compact flash Type 1 size or smaller

- An entire 802.11a NIC will be implemented by 1Q2001 in a PC-card format with single-sided component loading

4.2 MAC/PHY Throughput

Delivered data throughputs (after MAC and PHY overheads are subtracted) are 20.4 Mbit/s and 28.0 Mbit/s for 512 byte payloads

- **4.2.1. Minimum MAC/PHY Throughput**
  - In PCF mode the time to send a 512 byte packet is
  - Tdata = data + ack
    - data = preamble + PLCP + header + payload + CRC + SIFS
    - ack = SIFS + preamble + PLCP + header + CRC (**ignores piggybacking**)
  - For SIFS=9us, at 28.9 Mbit/s
    - Tdata = 200.4 us == 5792 bits
    - data = 4096 bits
  - efficiency = 71%
  - throughput = 20.4 Mbit/s
- 4.2.2. High End MAC/PHY Throughput
  - same calculation for 43.3 Mbit/s link
  - efficiency = 65%
  - throughput = 28.0 Mbit/s

4.3 Frequency Band

Same as 802.11a - 5GHz U-NII bands

- The 5 GHz Unlicenced National Information Infrastructure bands are
  - low band 5.15-5.25 GHz
  - mid band 5.25-5.35 GHz
  - high band 5.725-5.825 GHz

4.4 Number of Simultaneously Operating Full Throughput PANs

Twelve full rate simultaneously operating PANs can operate in one POS;
OR
We can almost tile the world twice over with 28.9 Mbit/s full rate PANs.

- Co-channel interference limits determine a minimum distance before a channel can be reused
- Reuse distance depends on the rate of increase of path attenuation with distance
- For a path loss exponent of 3.1 and hexagonal cells,
  - 10 channels are required for 43.3 Mbit/s D8PSK uncoded mode
  - 7 channels are required for 28.9 Mbit/s D8PSK R=2/3 trellis coded mode

Number of channels calculation

Approximate formula for number of channels to achieve maximum rate in each cell

- The number of channels N is determined using

$$N \approx \frac{1}{\Delta}\left[(\alpha Z)^{1/\gamma} + 1\right]^2$$

where,

- Δ is equal to 2 for square cells, 3 for hexagonal cells
- α is 1 for co-channel interference
- Z is C/N noise or interference limit (power linear form)
- γ is the propagation path loss exponent

4.5 Signal Acquisition Method

The system requires AGC, coarse timing sync and coarse frequency acquisition. It avoids the need for fine lock by the use of only differential modulation

- AGC based on fast RSSI and receiver gain control performed digitally well within the A16 preamble sequence
- coarse timing and frequency acquisition using A16 symbols
- differential phase reference provided by D64 symbol (with its D8 cyclic extension)

4.6 Range

Range for 1mW Tx power, 0 dBi Tx antenna gain, 0 dBi Rx antenna gain, 7 dB Rx NF and path loss based on ITU P.1238 exceeds 10 m for all rates

- Range for 14.4 Mbit/s signal field exceeds 18m
- Range for 28.9 Mbit/s link exceeds 13m
- Range for 43.3 Mbit/s link exceeds 10m
- (see earlier tables)
  - *ITU-R Recommendation P.1238 (1997) - PROPAGATION DATA AND PREDICTION MODELS FOR THE PLANNING OF INDOOR RADIOCOMMUNICATION SYSTEMS AND RADIO LOCAL AREA NETWORKS IN THE FREQUENCY RANGE 900 MHz TO 100 GHz*
  - The basic model has the following form:

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_f(n) - 28 \quad \text{dB} \qquad (1)$$

  - where:
  - N : distance power loss coefficient
  - f : frequency (MHz)
  - d : separation distance (m) between the base station and portable
  - L_f : floor penetration loss factor (dB)
  - n : number of floors between base and portable.

4.7 Sensitivity

Minimum sensitivity is -78 dBm

- The minimum sensitivity for the coded modulation at a BER of 1e-5 (a PER ~1%) is -78 dBm.
- This includes a NF of 7dB and an implementation loss of 1 dB and measurement at the antenna connection point

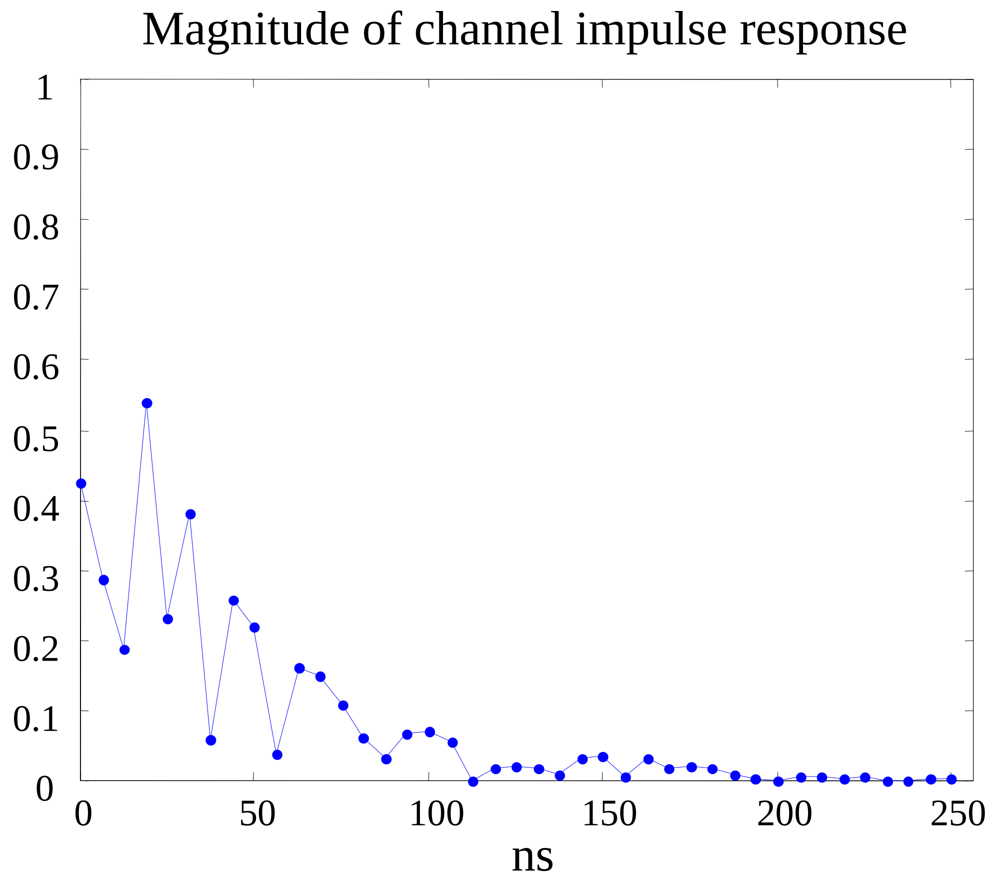
4.8 Multipath Immunity

The delay spread tolerance is better than Trms = 40ns

- ***4.8.2. Delay Spread Tolerance***
  - *Guard time is 400ns ie longest multipath is 400ns before intersymbol interference*
  - *This will give at least Trms = 40ns for an exponentially decaying model*

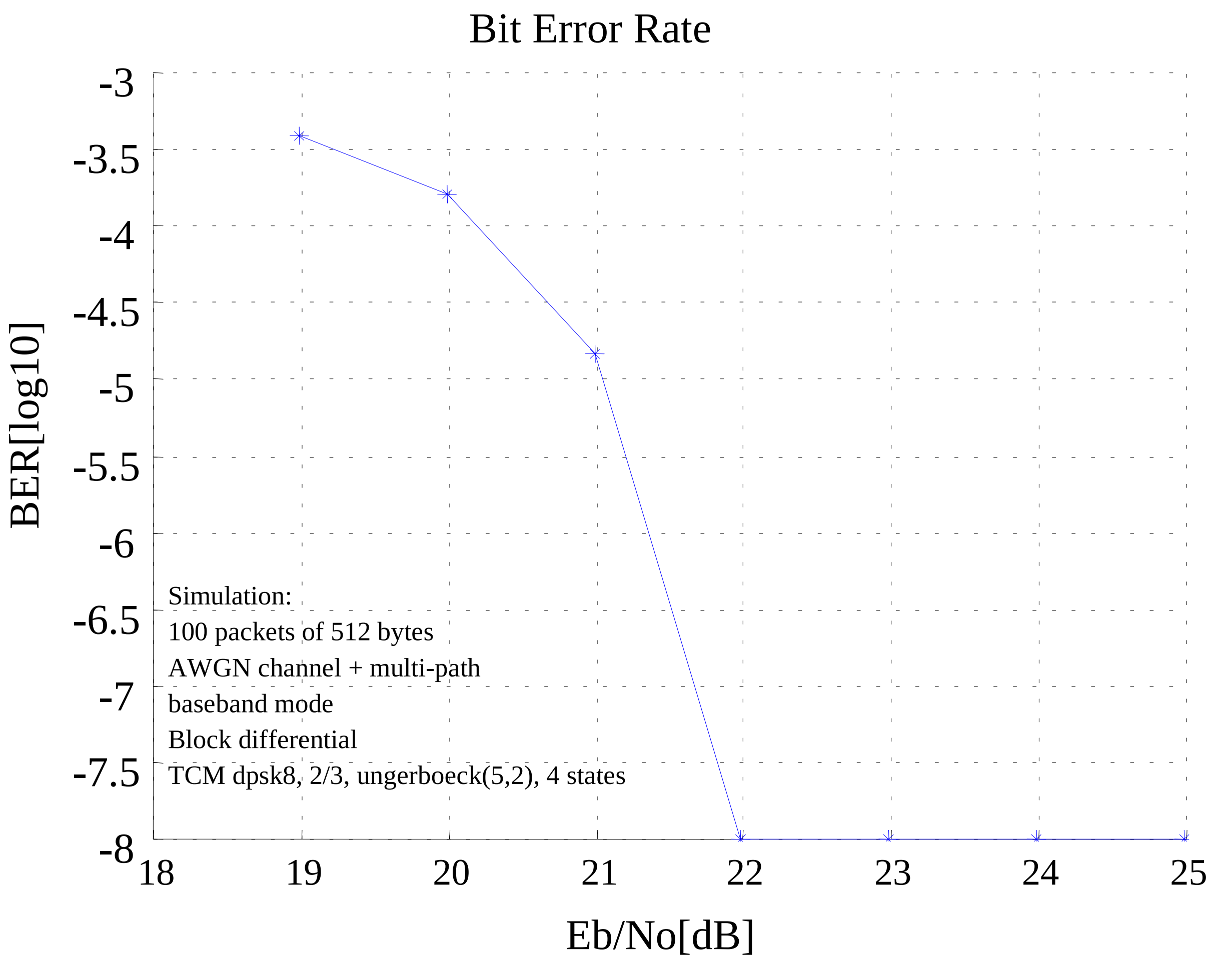
4.8 Multipath Immunity

Channel with Trms = 25ns generated according to environment exponential model in section 4.8.1



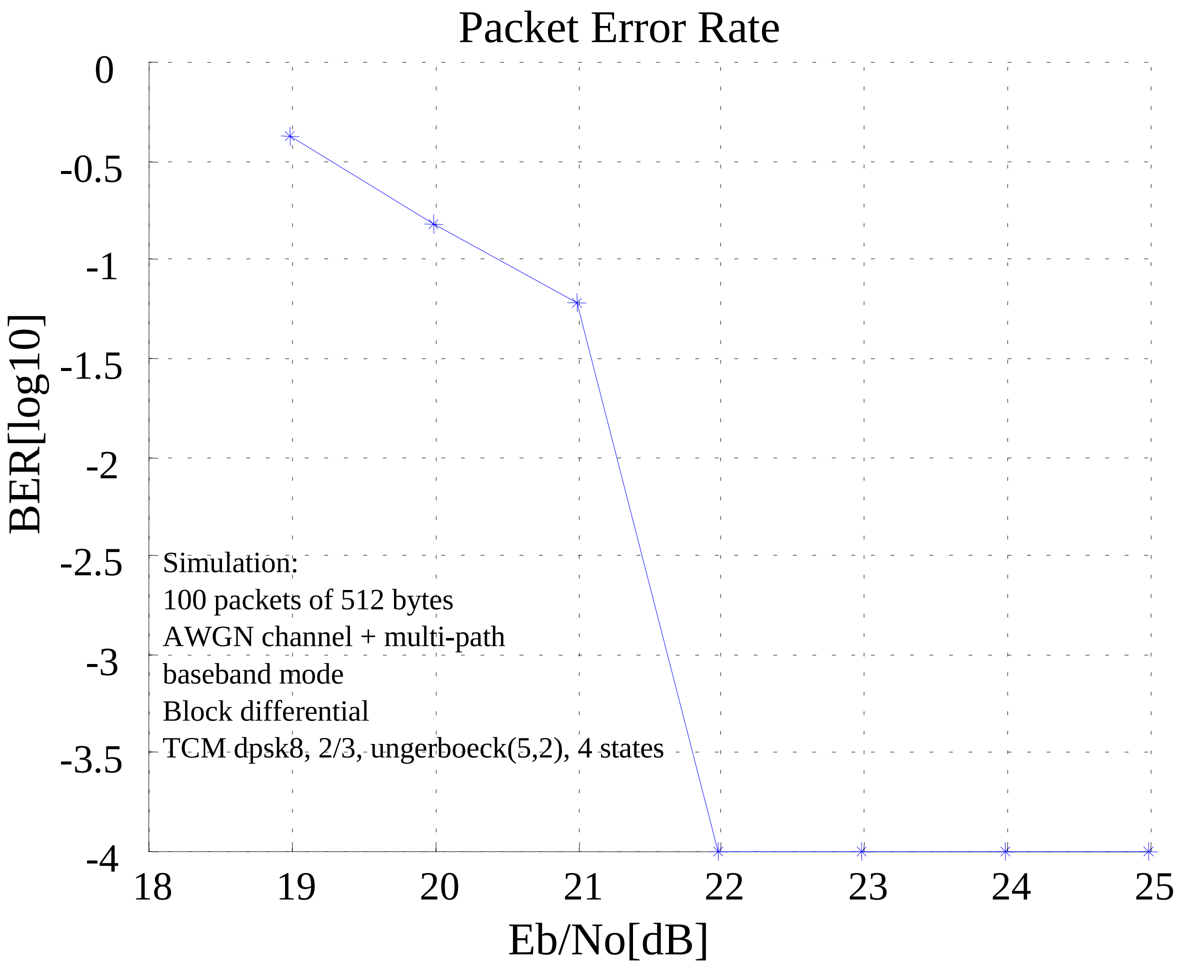
4.8 Multipath Immunity

BER for 28.9 Mbit/s rate and Trms=25ns



4.8 Multipath Immunity

PER (512 byte) for 28.9 Mbit/s rate and Trms=25ns



4.9 Power Consumption

Peak power is ~1.2W Receive and 1W Transmit based on a current implementation. Circuit optimization and process improvements can yield major power savings. Average power is reduced substantially by MAC power saving modes - factor may be 10 or more.

Rx (mW)	*Tx (mW)*	*2000 est*
177		RF Rx
	207	RF Tx
99	99	VCOs
	126	Baseband Tx
153		Baseband Rx
300		ADCs
	40	DACs
200	200	RAM
300	300	MAC
1229	972	Total mW

General Solution Criteria Comparison Values

CRITERIA	REF.	Comparison Values		
		-	Same	+
Unit Manufacturing Cost ($) as a function of time (when product delivers) and volume	2.1	> 2 x equivalent Bluetooth 1	1.5-2 x equivalent Bluetooth 1 value as indicated in Note #1 ***Notes:*** 1. Bluetooth 1 value is assumed to be $20 in 2H2000. 2. PHY and MAC only proposals use ratios based on this comparison	< 1.5 x equivalent Bluetooth 1
Interference and Susceptibility	2.2.2	*Out of the proposed band:* Worse performance than same criteria *In band:* -: Interference protection is less than 25 dB (excluding co-channel and adjacent channel)	*Out of the proposed band:* based on Bluetooth 1.0b (section A.4.3) *In band:* Interference protection is less than 30 dB (excluding co-channel and adjacent and first channel)	*Out of the proposed band:* Better performance than same criteria *In band:* Interference protection is less greater than 35 dB (excluding co-channel and adjacent channel)
Intermodulation Resistance	2.2.3	< -45 dBm	-35 dBm to –45 dBm	> -35 dBm
Jamming Resistance	2.2.4	Any 2 devices listed jam	Handle Microwave, 802.15.1 (2 scenarios) and 802.15.3	Also handles 802.11 (a and/or b)

General Solution Criteria Comparison Values

CRITERIA	REF.	Comparison Values		
		-	Same	+
Multiple Access	2.2.5	No Scenarios work	Handles Scenario 2	One or more of the other 2 scenarios work
Coexistence (Evaluation for each of the 5 sources and the create a total value using the formula shown in note #3)	2.2.6	*Individual Sources:* 0% *Total:* < 3	*Individual Sources:* 50% *Total:* 3	*Individual Sources:* 100% *Total:* > 3
Interoperability	2.3	False	True	N/A
Manufactureability	2.4.1	Expert opinion, models	Experiments	Pre-existence examples, demo
Time to Market	2.4.2	Available after 1Q2002	Available in 1Q2002	Available earlier than 1Q2002
Regulatory Impact	2.4.3	False	True	N/A
Maturity of Solution	2.4.4	Expert opinion, models	Experiments	Pre-existence examples, demo
Scalability	2.5	Scalability in 1 or less than of the 5 areas listed	Scalability in 2 areas of the 5 listed	Scalability in 3 or more of the 5 areas listed

MAC Protocol Criteria

CRITERIA	REF.	Comparison Values		
		-	Same	+
Transparent to Upper Layer Protocols (TCP/IP)	3.1	FALSE	TRUE	N/A
Unique 48-bit Address	3.2.1	Not Qualified (required by 802)	Essential	N/A
Simple Network Join/UnJoin Procedures for RF enabled devices	3.2.2	Extended procedure for joining network	802.15.1 style join as specified in sections 8.10.6, 9.3.23 and 11.6.5.5	Enhanced self-configuration of network
Device Registration	3.2.3	Requires manual configuration	802.15.1 style registration as specified in sections 8.10.7 and 11.6.5.1-4.	Auto registration based on profile
Minimum delivered data throughput	3.3.2	20 Mbps minus MAC overhead	20 Mbps	> 20 Mbps
High end delivered data throughput (Mbps)	3.3.3	20 – 39 Mbps	40 Mbps	> 40 Mbps

MAC Protocol Criteria

CRITERIA	REF.	Comparison Values		
		-	Same	+
Data Transfer Types	3.4	Asynchronous only	Asynchronous or Isochronous	Mixed Mode (Asynchronous & Isochronous simultaneously)
Topology	3.5.1	Point-to-Multipoint only	Point-to-Multipoint & Point-to-Point (with no Peer-to-Peer)	Point-to-Multipoint, Point-to-Point & Peer-to-Peer
Max. # of active connections	3.5.2	< 7	7	> 7
Ad-Hoc Network	3.5.3	FALSE	TRUE	N/A
Access to a Portal	3.5.4	FALSE	TRUE	N/A
Master Redundancy	3.6.2	FALSE	TRUE	N/A
Loss of Connection	3.6.3	FALSE	TRUE	N/A

MAC Protocol Criteria

CRITERIA	REF.	Comparison Values		
		-	Same	+
Power Management Types	3.7	Does not support power savings modes	Supports 802.15.1 power savings modes as specified in sections 8.10.8.2-4 and 11.6.6.1-5	Enhanced power savings modes
Power Consumption of MAC controller (the peak power of the MAC combined with an appropriate PHY)	3.8	> 1.5 watts	Between .5 watt and 1.5 watts	< .5 watt
Authentication	3.9.1	No authentication	802.15.1 style authentication as specified in sections 8.14.4 and 9.3.2	Enhanced authentication at MAC layer
Privacy	3.9.2	No encryption	Encryption as specified in 802.15.1 section 8.14.3 and 9.3.6	Packet encryption
Quality of Service	3.10	No provisions for QoS	Equivalent to QoS specified in 802.15.1 section 9.3.20 , 10.6.3 and 11.6.6.6	802.11e level of QoS

Phy Protocol Criteria

CRITERIA	REF.	Comparison Values		
		-	Same	+
Size and Form Factor	4.1	Larger	Compact Flash Type 1 card	Smaller
Minimum MAC/PHY Throughput	4.2.1	20 Mbps (without MAC overhead)	20 Mbps + MAC overhead	> 20 Mbps
High End MAC/PHY Throughput (Mbps)	4.2.2	20 – 39 Mbps	40 Mbps + MAC overhead	> 40 Mbps
Frequency Band	4.3	N/A (not supported by PAR)	Unlicensed	N/A (not supported by PAR)
Number of Simultaneously Operating Full-Throughput PANs	4.4	< 4	4	> 4
Signal Acquisition Method	4.5	N/A	N/A	N/A
Range	4.6	< 10 meters	$\geq$ 10 meters	N/A
Sensitivity	4.7	N/A	N/A	N/A
Delay Spread Tolerance	4.8.2	< 10 ns	25 ns	> 50 ns
Power Consumption (the peak power of the PHY combined with an appropriate MAC)	4.9	> 1.5 watts	Between .5 watt and 1.5 watts	< .5 watt